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22 Nov. 1888.

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Prof Asa Gray
with the kind regards of
J S Newberry

EARTHQUAKES.

BY
PROF. J. S. NEWBERRY.

From School of Mines Quarterly, Vol. VIII, No. 1,
October, 1886.

PRINTED FOR THE AUTHOR.

NOV 1881

Mrs. Asa Gray

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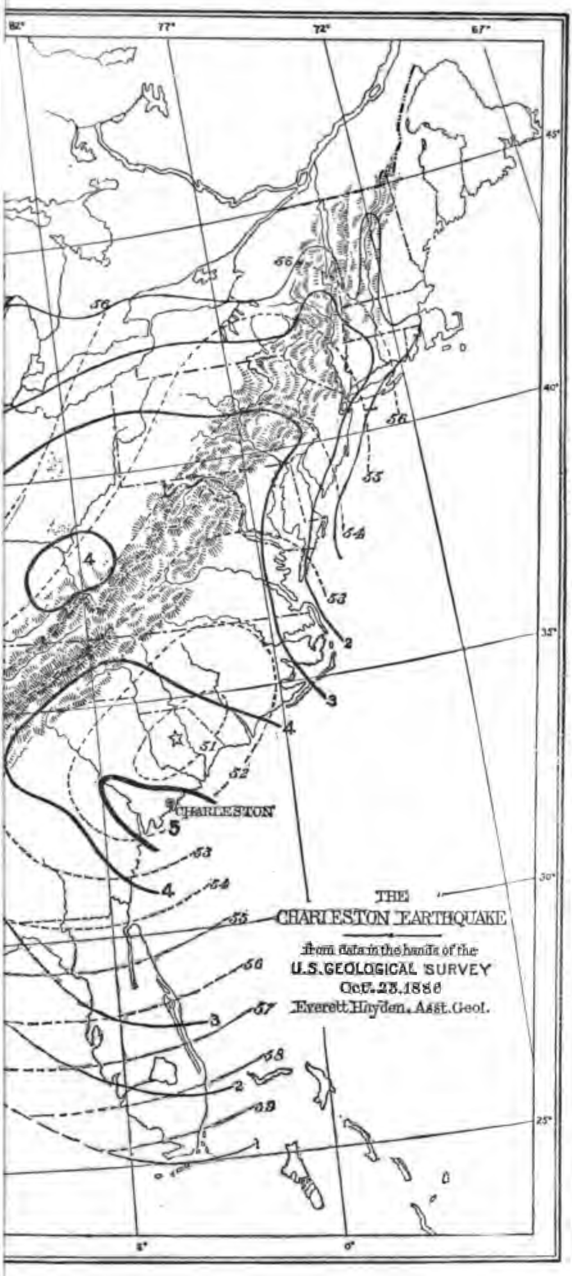
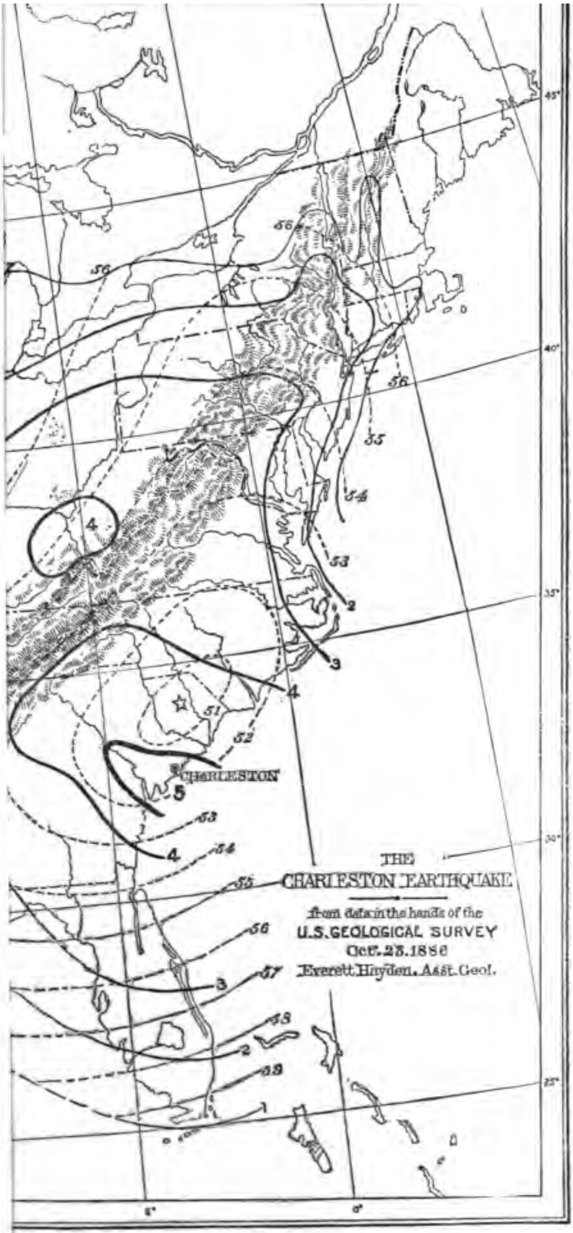


THE
CHARLESTON EARTHQUAKE

from data in the hands of the
U.S. GEOLOGICAL SURVEY
Oct. 23, 1886
Everett Hayden, Asst. Geol.

~~Math. 783~~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EARTHQUAKES.

BY PROF. J. S. NEWBERRY.

FROM all quarters have come to me inquiries about the earthquake in Charleston. Because I am a teacher of geology it has been taken for granted, quite gratuitously, that I know or ought to know, all about the earth of which the structure and history are the geologist's special objects of study. That he knows more about these than other people is possible, but that he knows all about them is unfortunately far from true. It is, however natural that I should be appealed to for information in regard to what is the most striking of all terrestrial phenomena; and while I do not claim nor accept the title of "Professor of Earthquakes," which one correspondent seriously gives me, I acknowledge it as a part of my duty to satisfy, as far as I am able, the demand which has been made by the public. I shall, therefore, attempt to give to the readers of the QUARTERLY on the following pages a brief review of what is known and believed in regard to the phenomena and causes of earthquakes by those whose opinions on this subject are most worthy of confidence.

There is something particularly unsettling and terrifying in the upheavals and undulations of what we call *terra firma*, because it has been accepted as the type of stability. To men of all countries and ages, civilized and savage, the earthquake has been a peculiar terror and mystery. Even the most stoical and reasonable have lost their self-possession when they have felt the solid earth heaving and groaning beneath them; and in the countries where earthquakes are most common, the horror and dread they inspire are never lessened by familiarity, but every new shock produces fresh and increased alarm. It is not surprising, then, that in a region like Eastern North America, which has been supposed to be exempt from serious catastrophes of this kind, the occurrence of such an event as that which recently took place at Charleston, has produced a profound and wide-spread sensation. It has not only called out strong expressions of sympathy with the sufferers, but has excited the keenest desire to know all that can be known of this and similar phenomena. It has been the common subject of conversation throughout the land. The journals have been full of descriptive details. Scientists of all kinds have been interviewed, and been made to give their views, if they had any; if not they have been supplied to them. As a consequence, many wild and contradictory statements have been made, and so many theories advanced, that the public has hardly known what to believe.

Yet earthquakes are neither novel nor mysterious, but are among the most common and simplest of terrestrial phenomena; they have certainly recurred at frequent intervals throughout all geological time of which we have any record, and it is probable that now, not an hour, perhaps not a minute, passes, but more or less violent vibrations take place somewhere on the earth's surface. In later years, earthquakes have been carefully studied in many countries by geologists and physicists, and the conclusions reached have been so generally harmonious that there is now very little difference of opinion as to their cause, and the manner in which this cause operates.

Briefly told, *an earthquake is a movement caused by a shrinking from the loss of heat, of the heated interior of the earth, and the crushing together and displacement of the rigid exterior as it accommodates itself to the contracting nucleus.*

I cannot, in the limited space now at my disposal, give anything more than a summary of the facts upon which this statement rests, but I may say that they are so numerous and significant that the conclusion deduced from them, enunciated in the above paragraph, is not only convincing but inevitable. I will briefly notice some of these facts.

From observations in mines, and from deep borings, from hot springs and volcanoes, we have learned that the interior of the earth is intensely hot. The most satisfactory data for this conclusion are furnished by wells and mines. These are located in all the great divisions of the earth's surface: China, India, Australia, Africa, Europe, and North and South America, all have their mines or deep borings, which give fairly harmonious testimony upon this subject. They prove that after passing the plane of invariable temperature, beyond which the alternations of the seasons are not felt, the heat increases about 1° Fahr. for every 50 feet; for example, the well in the grounds of the Lunatic Asylum at St. Louis, is 3843 feet in depth; at 3200 feet, where the temperature was last observed, it was 107°; the State House well, at Columbus, Ohio, is 2775 feet deep, and at 2575 feet the temperature is 88°. The artesian well at Louisville, Kentucky, is 2080 feet deep, and the temperature at the bottom is 82° summer and winter. Other wells bored in the Valley of the Mississippi and in the Eastern States furnish similar data.

In Europe, many deep mines and wells have afforded facts coincident with those I have reported from this country; for example, the well of Grenelle, at Paris, is 1800 feet deep, and the water which flows from it has a temperature of 82° Fahr., while the mean annual temperature at the surface is 51°. A well bored at Sperenberg, Germany, to the depth of 4172 feet has a temperature, at 3390 feet, of 115.5° Fahr., while a well at Schladenbach, 5286 feet deep, has a temperature at bottom of about 131°. Wells in China, India, and Australia, show a corresponding increase of temperature in descent, although few quantitative observations have been made there.

There are some exceptions to the rule that the temperature increases at the rate of 1 degree for every 50 feet in descent; for example, in the mines on the Comstock Lode, Nevada, at the depth of 3200 feet the temperature is 160° Fahr., an increase of about 1 degree for every 29 feet of descent. This case and similar ones at Monte Massi, in Tuscany, and at Buda-Pesth, Hungary, are quoted by Professor Judd, in his *Volcanoes*, and are considered of sufficient importance to invalidate the evidence of thousands of other mines and wells. But the exceptions only prove the rule. The wells mentioned are located in regions which not long since, geologically speaking, have been the scenes of violent volcanic action. The surface of the country is occupied by vast sheets of lava, hot springs abound there, and it is evident that the subterranean fires are not yet extinguished. A boring on the flanks of Mt. Etna would be a still more striking exception to the rule of one degree for every 50 feet, and would be equally legitimate evidence against it.

Excluding these abnormal cases, which really have no bearing on the question, the irregularities in the rate of increase in temperature are not greater than those which might be caused by differences in the conductivity of the rocks passed through. The deep wells of Sperenberg and Schladenbach—which were bored in part to test this question, and have been the most carefully observed of any—have given the most convincing evidence of the truth of the theory of intense internal heat.* The case cited by Professor Judd (*Volcanoes,* p. 341), "a deep well in Buda-Pesth, in which there was a decline of temperature below 3000 feet," is probably a mistake or a fraud. The same thing happened at the deep well at St. Louis, in which the temperature increased regularly to the depth of 3200 feet, where it was 107° Fahr. Below that the contractor reported the temperature declining, *because the directors were about to stop the work, partly on account of the warmth of the water!* To prevent exposure of the fraud iron rails were dropped into the well.

It may then be considered as established that all over the earth's surface, except in volcanic districts, the temperature increases about one degree Fahr. for every 50 feet descent. It is evident that should this rate of increase continue the temperature at the depth of 50 miles would be sufficient to melt all known substances, and the first conclusion from the observations of temperature in mines and wells was that the solid portion or crust of the earth could not be more than 40 or 50 miles in thickness, and it was proclaimed that we were living on a film of solid matter, floating on a sea of molten rock. The comparative stability, however, of the earth's figure—the little effect produced by the attraction of the sun and moon—have led to the conclusion that the earth's crust is thicker than this, and it has been suggested that while the accuracy of the observations on the increase of temperature to the depth of one mile cannot be questioned, it is possible that the rate of increase to that depth is not constant below; that the increment may diminish, and therefore, the temperature of fusion may only be reached at a greater depth than has been supposed.

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* Some of the temperatures in the Schladenbach well are as follows:

Depth in Metres.	Temp. Fahr.	Reaum.
1266	113.5°	36.2°
1296	115.°	36.9°
1326	116.8°	37.7°
1356	119.3°	38.8°
1386	121.3°	39.7°
1416	122.9°	40.4°
1506	127.2°	42.3°
1566	128.3°	42.8°
1596	130.1°	43.6°
1626	131.°	44.°

It has also been shown that the melting point of many substances is raised by pressure, and therefore, that the enormous weight of the overlying rocks, equivalent to 792,000 lbs. to the square foot for every mile, may hold in coerced rigidity a considerable zone of the earth's mass composed of materials that would melt and flow on the surface at a much lower temperature than that which they now endure in a solid form. Accepting, then, the conditions imposed on the old theory of the state of the interior of the earth by pressure and the possible diminution of the increment of temperature, we may suppose that the solid crust is considerably thicker than was formerly supposed. That it is relatively thin, however, is indicated by facts which will be cited further on.

The increase in temperature observed in mines and deep borings means that the heat of the interior of the earth is constantly escaping to the surface, where it is radiated into space. If the outer crust were a perfect non-conductor the materials within it would always maintain a condition of thermal equilibrium throughout. It is thus evident that the process of refrigeration is progressive, and from the time when the first film of solid matter dimmed the brightness of the "glittering globe of liquid fire" the crust formed at the surface has been constantly increasing in thickness, while by the loss of heat, which is an expansive force antagonistic to gravity, the volume of the earth has been as constantly diminishing. But since the outer crust has lost its inherent heat and has become solid it no longer shrinks, though the loss of volume goes on incessantly in the intensely heated, but gradually cooling interior. As the nucleus contracts the solid crust cannot accommodate itself moment by moment to the loss of volume, for it resists by its rigidity and is brought into a state of strain. This is relieved from time to time, whenever it passes the resistance of the materials composing the crust, by a crushing together and displacement of the surface rocks. These are *faulted* or *folded*; that is are either thrown into great waves by lateral pressure, or the arches are broken and fissures are produced at right angles to the line of thrust. The rocks forming the sides of these fissures slide on each other, forming what geologists call *faults*, in which the "throw" or displacement sometimes amounts to many thousand feet. Earthquakes, mountain chains and volcanic eruptions may all be considered as consequences of this readjustment. Mountain chains are great lines of fracture in the earth's crust along which rocks before nearly horizontal are raised into ridges by lateral pressure. They have been compared, not inaptly, to the wrinkles formed in the rind of a fruit when it loses its volume by drying. Every mountain chain shows many folds and faults; in the Alleghanies the folds are noticed by every traveller, and few better examples of folded strata are seen anywhere than those which border the gorge which cuts through the ridges from Cumberland to Frostburg, Maryland. The faults are less conspicuous and would hardly be detected except by a geologist, but they are very numerous, and in some of them the displacement is more than 20,000 feet. The Wasatch Mountains in Utah—one of the boldest ranges on the continent—owe their relief mainly to a fault which runs nearly north and south through the middle of the Territory. The country west of this fault is thrown down and that on the east raised to form a wall 5000 to 7000 feet high.

It is evident that the folds and fractures seen in every mountain belt could not have taken place without great disturbance of the surrounding country. And as they have been formed, not all at once, but each by itself, and each one by many paroxysms, an almost infinite series of earthquakes is recorded in the structure of every mountain chain. A large number of earthquakes of modern times have been attended by changes of topography which have remained as evidences of the displacements which caused the vibrations. Sometimes a line of coast was raised above the ocean level, sometimes mountains or cliffs split and fell, sometimes fissures and faults were formed many miles in length.

Another thing about mountain chains is not so generally known as that they are lines or belts of folded and fractured rocks; and that is that they are the products not of moments or even years but of ages. The lines of fracture which are marked by mountain chains are ever, after the first disruption, lines of weakness, where the resistance to lateral pressure is diminished, and where the strain of large unbroken areas is relieved from time to time by displacements, necessarily attended by earthquakes. I have sometimes compared them to hinges on which the great tables of the earth's crust turn with constantly changing angles. Generally mountain chains may be said to grow by the constant or paroxysmal elevation of their arches, the increase in the throw of their faults. This growth would be much more apparent than it is if it were not that the mountain chains receive a far greater precipitation of moisture than the lowlands, and erosion, which is the opposing force to elevation, counteracts its effects. The East Indian geologists estimate that in the Himalayas the process of elevation is going on constantly and that it is at least equal to the loss from denudation.

The application of all that has gone before to the Charleston earthquake is simply this: that we learn from the facts cited that displacements are constantly taking place in the crust of the earth the world over, and as these affect rigid and resistant masses of rock they are produced *per saltum*, that is in paroxysms. The strain accumulating until it overcomes the resistance is relieved in one or many efforts, each of which is attended by an earthquake vibration of greater or less force. The country bordering a disturbed belt is sure to feel the effects of subterranean movements more frequently than plains and plateaus remote from mountains. Every year we hear of local disturbances in the Southern Alleghanies, and Bald Mountain has been the scene of so many that it has come to be looked upon with awe and apprehension by the people in the vicinity. So along up the Atlantic slope of the Alleghanies there have been many earthquakes since the country was occupied by the whites. Not a year passes that we do not hear of several in New England, the Middle or Southern States. As the population increases, the number of observers is multiplied and the number of structures liable to damage constantly added to; so that such phenomena now attract more attention and cause greater destruction than formerly. In New England the best record of earthquakes has been kept, and if any one will look over a file of newspapers published at Boston or Hartford he will find that within the last century a very large number of earthquake shocks or vibrations are noticed. Earlier than that we must depend upon town records or private correspondence. From these we learn that in 1727 the country about Newburyport, Mass., was shaken up, very much as Charleston has recently been, but in that region there were then but few buildings and those of wood; so that the damage was comparatively small.*

Two years ago New York City suffered an earthquake shock, but fortunately not a severe one. It occurred about two o'clock

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* Since this paper was written I have received "Historical Notes on the Earthquakes of New England from 1638 to 1869," by Mr. William T. Brigham, published in the Memoirs of the Boston Society of Natural History, 1869. This contains notes upon two hundred and thirty-one earthquakes, with many interesting details.

Sunday afternoon, the 10th of August. I was sitting alone in my room in the College, where all was perfectly still; suddenly I heard a heavy rumbling sound like that of a passing loaded wagon ten times magnified. At the same time the building began to vibrate, the windows rattled and some light objects were disturbed and fell to the floor. I was sensible of a tremor that not only jarred but swayed my body and caused my book to vibrate and swing in my hand. I recognized the nature of the phenomena at once, observed the time and made a note of it. Subsequently going into the geological cabinet I found palpable evidence of the force of the vibrations. In a case occupied by specimens of marble, many of which were set on edge against the back of the case, all such were thrown down and some were broken. As the back of the case was toward the north, this proved that some of the vibrations were from that direction. This earthquake was noticed by a number of observers, and their testimony showed that the area affected was, as usual, elliptical in outline, and extended from Washington, D. C., to Portsmouth, Me., and from Harrisburg, Pa., to the Atlantic.

In the Old World observations on earthquake vibrations have been reduced to a system, and instruments called Seismographs or Seismometers have been devised, which make an automatic record of the time, direction and force of the vibrations. Where such instruments are scattered over a country it is evident that the outline of the area affected by an earthquake shock, as well as the geographical position and depth of the centre of motion, may be accurately determined.

In Japan, where earthquake vibrations are almost incessant, an extended system of observations has been instituted by Prof. Milne, which are likely to throw much light upon this subject.

In this country there are few Seismometers, and no carefully regulated system of observation has been yet adopted, but it is probable that the one good effect of the Charleston earthquake will be to excite an interest in such phenomena that shall result in the organization of a thorough system of observation. The officers of the Geological Survey and Signal Service Bureau are taking an active interest in the matter, and it is probable that observations on the movements of the earth will be added to those they are now making on the movements of the atmosphere.

When the data already collected in regard to the Charleston earthquake shall have been tabulated, it will doubtless be found that the displacements which occasioned the vibrations were located along a line parallel with the Alleghanies and at a depth of 10,000 to 20,000 feet, not under but westward of the city.

Inasmuch as no great change took place on the surface of the land in South Carolina, it has been suggested that the seat of the movement was under the ocean, and that important changes may have taken place in the topography of the sea bottom. It is quite certain, however, that such was not the case; for any considerable movement beneath the ocean in the vicinity would have resulted in a great wave upon the shore, such as have attended many other earthquakes, viz., that of Kingston, Jamaica, in 1692, of Lisbon in 1755, or that of Arica, Peru, in 1868. No wave at all is reported on the coast of South Carolina, though a distinct shock was felt on board a ship which had just left Charleston. This proves that the seat of the disturbance was not under the sea, but on the land, the vibrations passing from the land seaward. It is reported that a slight change in the depth of the water in Charleston Harbor has resulted from the earthquake, but no accurate observations have been made to test the truth of the report. In all probability the movement was in the old crystalline rocks beneath the comparatively modern deposits which underlie the surface, and consisted in a yielding to lateral thrust which ruptured and slipped some of the beds over others. Such fracture and movement would produce vibrations which would take the form of successive waves passing vertically, upward and outward in every direction from the focus of action. As the older rocks which underlie this region dip toward the east and have a strike north and south, an impulse produced by disruption would move north and south in continuous strata, and east and west through a succession of beds which would be less good conductors. Hence the area of vibration will doubtless be found to be an ellipse with its longest diameter north and south.

One fact reported from Charleston is very interesting if true, and that is that the railroads leading westward were shortened; the rails being arched much out of line. To straighten the roads, it is said to have been necessary to cut out " here one foot," " there two feet," etc. of the rails. This shortening, if verified and measured, would give a clue to the location and extent of the subterranean movements which produced the vibrations.

* *

The determination of the depth of the focus of action in earthquakes is generally a difficult problem from the lack of accurate observations. Where the angle of emergence of the earthquake-waves can be ascertained, even along a few lines, it is easy to fix the point where these lines intersect. In this way the depth of focus of many earthquakes has been determined. Mr. Mallet, who has made the most elaborate study of earthquake phenomena, gives the maximum depth at 8½ geographical miles and the minimum depth at 2¾ miles; but Dr. Oldham, late director of the Geological Survey of India, estimated the focus of action in the great Cachar (Bengal) earthquake of 1869 to be from twenty-five to thirty miles in depth.

The bursting out of temporary springs or fountains of water carrying quantities of sand has been mentioned as a remarkable feature in the South Carolina earthquake, but this is a phenomenon common to many earthquakes, and is specially noticed in the accounts we have of those of Newburyport of 1727, and New Madrid, 1811. It is, doubtless, due to the pressure exerted by the earthquake-wave on subterranean reservoirs of water, or the compression of water-bearing strata.

Another circumstance, which has excited some curiosity, is the twisting of chimneys and monuments on their foundations. This has been noticed among the consequences of many earthquakes, and it has been generally attributed to a gyratory movement of the earth, but Mr. Mallet has shown that this is not a necessary conclusion, but that an adhesion to one part of the foundation would cause a revolution of the superstructure about this point.

It will be noticed that, in the reports which have been given of the Charleston earthquake, there is an absence of all reference to the explosions which have been among the most striking and destructive phenomena of earthquake action in some localities. Thus in the description of the great earthquake of Riobamba, Equador, in which 40,000 persons perished, it is said that the bodies of many of the inhabitants were thrown upon a hill which rose to the height of 100 feet on the other side of a stream; and, during the earthquake of Chili, in 1837, a mast, planted 30 feet deep, was thrown out so that a round hole remained behind. These, which are called explosive earthquakes, have been confined to the vicinity of volcanoes and to districts bordering on the sea, and it is supposed that, by the disruption of the rocks, large quantities of water have been suddenly brought into contact with melted lava. Steam has played an important part in most volcanic eruptions, though, as a secondary, and not, as often supposed, a primary cause. Masses of molten matter, welling up through fissures in the earth's crust, must necessarily come in contact with subterranean reservoirs of water, or with strata saturated with moisture. In the vicinity of the sea, too, where most volcanoes are located, water may be admitted in the manner just described. In all these cases, steam would be generated in such quantities as to make this an efficient adjuvant to the lava flood in producing disruption, upheaval and vibrations of the rocks. The absence of these violent features in the earthquakes of the country bordering the Alleghany belt, proves that volcanic action has had nothing to do with them, and shows that, like a vast majority of earthquakes elsewhere, these have been, as Dana says, " incidental phenomena in the process of mountain building;" that is, they are sensible signs of the lateral movement of the earth's crust which results in the crushing, folding, faulting, elevation and metamorphism which are distinctive features of all mountain belts and chains. Where this action takes place on a grand scale, and involves the entire thickness of the earth's crust, mountain chains of great elevation, length and breadth are the result, and, through profound fissures opened to the zone of molten material below, lava rises and overflows. In the Triassic age, such deep fissures were opened along the Atlantic border of the continent, as is attested by the trap sheets and dikes which extend interruptedly from Nova Scotia to the Carolinas. At that time, the whole coast must have been shaken with earthquakes of great violence, and much of it devastated by lava-floods. Since then, the earth's movements have been only the relatively gentle vibrations caused by the yielding of the flexed and fractured rocks of the upper portion of the crust to the ever acting and resistless thrust of the great unbroken tables of the Mississippi Valley and the Atlantic basin.

EARTHQUAKES AND VOLCANOES AS MEASURES OF THE THICKNESS OF THE EARTH'S CRUST.

As is mentioned in the early part of this article, the first result of the discovery of the law of increase of temperature in going toward the centre of the earth was the conclusion that the solid crust was not more than 50 miles in thickness, and below that was a sea of fluid or semifluid molten matter. Then mountain chains were supposed to be the result of the crushing together of solid sheets of rock as they followed the cooling and shrinking interior. The coat becoming too large, and adhering to the body, must wrinkle as the body shrank. Volcanic eruptions were supposed to be the oozing out of molten matter from the not distant zone of fused material, and all was harmonious in the geological world. Then came Professor Hopkins, Archdeacon Pratt and Sir William Thompson, in the character of disturbers of the public peace; they said that the crust would be broken up by tides if it was as thin as supposed; that the shell would be pulled about on the fluid nucleus by the attraction of the moon on the equatorial protuberance; and, finally, that the tenacity with which the figure of the earth was maintained under the varying pull of the sun and moon made it necessary to suppose that it was, as a whole, as rigid as a globe of glass, or even of steel. Sir William Thompson conceded, with some hesitation, that the crust of the earth might not be more than 2500 miles in thickness; further than that, he would not go. Since that time, awed by his great and well deserved fame, geologists have generally accepted the conditions he imposed upon them, and there has been a terrible struggle to reconcile volcanoes, earthquakes and the flexibility of the earth's crust with a solid interior. Some have gone back to Sir Humphry Davy's theory, that volcanoes were the product of intense chemical action in certain circumscribed portions of the earth's mass; and others have supposed that, between a thick external crust and a solid interior there was an intermediate zone of fused matter from which volcanic ejections emanated. Mallet, who has displayed great learning and ability in his various papers on volcanoes and earthquakes, forbidden by Sir William Thompson's dictum from drawing molten matter from the interior of the earth to operate his volcanoes, contrived a method of manufacturing it on the spot. He proposed a theory that all the phenomena of vulcanism are due to the arching of the exterior strata composing the earth's crust, their final yielding to gravity and crushing down on to the contracting interior; the conversion of motion into heat producing all the thermal phenomena.

A fatal defect in this theory is that it gives no reason for the localization of the heat along the line of fissure from which the lava flows. All parts of the masses on either side must share in the motion and should also share in the heat, and we must look elsewhere for an explanation of the phenomena.*

There would have been no question of the truth of the old theory of vulcanism if it had not been raised by the physicists whose names have been mentioned, and it can now be seen that their objections have little force. Delaunay, of Paris, and Hennessy, of Dublin, have shown that the premises assumed by Thompson, Hopkins and Pratt in their attempted refutation of the old theory of a comparatively thin crust are not those of nature, and that their conclusions are, as a consequence, irrelevant and valueless. Their objections were aimed at an incompressible fluid interior and an elastic crust; conditions which do not and could not exist. Beside this there must be a viscous zone of considerable thickness in which the transition from the solid crust to the liquid interior is very gradual; and it is highly probable that the matter of this viscous zone is not only not itself affected by tidal movements, but that it acts as a buffer between the liquid interior and the solid crust. It should be remembered that the moon's attraction—the chief motor in oceanic tides—is a force applied to a surface moving at the equator about a thousand miles an hour. Even a fluid as thin as water refuses to obey instantly an attracting body. The tidal wave of the ocean is always considerably behind the moon, and in some places where obstructed by topographical features it doesn't reach its destination until some time the next day. It is easy to see that in a tarry, pitchy mass the response to the moon's attraction would be far less prompt, and also that the tidal waves in zones of different depths and densities would not coincide, and might completely neutralize each other.

Every boy knows that if a flat rock is thrown from a cliff on to water some distance below, it is shattered almost as though it fell upon a solid; but the velocity of a falling body *in vacuo* is 16 feet the first second, 48 the second, etc., and with the resistance of the air, it is doubtful whether a stone thrown from a cliff 100 feet high reaches the water with a velocity greater than 50 feet a second, while the velocity of impact, if we may use the expression, of the moon's attraction is nearly 30 times greater than that, or 1466 feet per second. The resistance which the internal friction of a viscous body would offer to a force applied with such velocity would be enormously greater. Hence we must conclude that the tidal movement in such a mass even at the earth's surface must be very small, and if, as is the case in the interior of the earth, that mass were condensed and constrained by the weight of a crust even a hundred miles in thickness, it would be inappreciable. It should be remembered that the force of gravity acting upon a column of matter one foot square and having the density of the materials composing the earth at the surface, that is 2½ times that of water, is 792,000 lbs. for every mile, or 79,200,000 lbs. at the depth of 100 miles. Such a pressure must greatly increase the density of matter of any kind. The average density of the earth is 5½ times that of water, and it is plain that in matter of this density and so situated not only a tidal wave would be impossible, but any attraction which is constantly and rapidly changing its point of bearing must be practically powerless to distort the figure of the earth.

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* In a review of Mr. Clarence King's report "On the Geology of the Country Bordering the Fortieth Parallel," the writer in 1879 suggested a simple explanation of the phenomena of vulcanism, viz., A slight arching of the crust of the earth along lines of fracture and elevation, in a measure relieves the pressure by which highly heated matter below is kept in coerced solidity. This relief of pressure causes the potential fluidity of this compressed matter to become actual, and thus reservoirs of lava are called into existence beneath the lines of fracture and arching. Finally the pressure from gravity being maximum under the tables of unbroken strata on either side, and minimum beneath the crown of the arches, this unequal pressure causes the lava to rise along the fissures and flow out in volcanic eruptions.

FLEXIBILITY OF THE EARTH'S CRUST.

It is difficult to imagine how the advocates of the theory of a solid globe can account for the formation of mountain chains, the loftiest and longest of which are quite modern, and it is not perhaps too much to say that these themselves are a refutation of their theory. It is evident that a heated solid globe, as it lost its heat, would either contract bodily as a red hot cannon ball does, or by the more rapid cooling of the outer surface, that would shrink faster than the interior, and crack in every direction; a process just the opposite from that which we find recorded in the earth's crust.

But there are other evidences of the flexibility of the earth's crust which are incompatible with the theory which ascribes to it great thickness. (1.) The lines of volcanoes which crown most great mountain chains are located along fissures which seem to be continuous for thousands of miles, and there is apparently good evidence that these fissures penetrate through the entire thickness of the solid crust. Sometimes the volcanoes are in simultaneous action for several hundreds of miles, and the materials ejected though showing much variety are often identical: facts incomprehensible on any other supposition than that they have been drawn from a common reservoir.*

(2.) Along all the coast lines the evidences of local changes of level now in progress, or included in the records of past time, are so numerous and striking, that the term *terra firma* seems singularly ill-chosen; for example, the shores of the Mediterranean abound in evidences of local depressions or elevation, or both, since it has been occupied by civilized man. Of these the temple of Jupiter Serapis at Baiæ, is one of the most famous, but by no means the only example.

On our own continent the southern portion of Greenland has been gradually sinking for several hundred years; Labrador and New Foundland are rising; Prince Edward's Island and Cape Breton, according to Gesner, have sunk many feet since they were first occupied by the whites. In Nova Scotia the land is rising; in Northern Maine it is sinking, as, also, at Cape Cod and Martha's Vineyard and on the shore of Long Island and New Jersey. Here the subsidence has locally varied from two to twelve feet during the last century. In the West Indies, there are many evidences of local change of level; in some cases, of elevation, others, of subsidence. In California, we find traces of recent and local flexures of the coast which are very striking; at San Diego is an old beach strewed with shells which have not yet lost their colors, twenty feet above the present sea-level. At San Pedro, the port of Los Angeles, the limestone rocks which form the sea cliffs are bored by *Pholas* eighty feet above the water; on the south shore of San Pablo Bay, at a height of twenty feet above the water, is a bank of oyster-shells, four feet in thickness; this descends toward the south, and disappears beneath the surface of San Francisco Bay. Puget Sound, with its many branches, is only the submerged valley of a great river which ran out to sea through the

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* Darwin mentions (Trans. Geol. Soc., March, 1838), that in the Andes the volcanoes Osorno, in lat. 40° S., Concagua, in 32° S., and Coseguina, in lat. 13° N., burst into eruption simultaneously on the 20th January, 1835. The more remote of the three are 3700 miles apart.

Straits of Fuca when the coast was much higher than now; but the shores are terraced to the height of 1600 feet above the present water-level; showing that, in recent times, they have been much lower than now. Similar facts with these have been reported from the shores of all the continents, and the islands afford more striking examples of the changes of level; the Windward Islands are only the summits of a lofty mountain chain which was once all above the sea-level, as is shown by the community of species in animals and plants. The Islands of the South Pacific are, also, the summits of mountains which have been gradually submerged as has been shown by Dana and Darwin. Coral reefs which are formed only within 150 feet of the surface, now extend down in continuous walls, 2000 feet below the water; the growth of the coral having kept pace with the gradual subsidence. Elisé Reclus, in *La Terre*, and Professor Prestwich, in his *Geology*, give maps, showing the fluctuations of level now in progress along coast lines, and whoever will examine these maps, will find it difficult to reconcile these oscillations of the land with a globe solid to its centre, or even with a thick crust. But the changes of level now taking place, proceed so slowly, that the record of 150 years, during which geological observations have been made, or even that of the long period covered by human history, is insignificant, compared with that of the geological ages. Indeed, historical geology is, for the most part, but a transcript from the monuments left by successive and local subsidences of the land, influxes of the sea, and the deposition of strata containing relics of the marine and terrestrial life of the epochs in which these inundations occurred. Scarce any portion of any continent is without traces of the presence of the sea, and, while some of these submergences were, doubtless, caused by great tides which ebbed and flowed from one hemisphere into the other, in the manner suggested by Adhemar, it can be easily shown that most of them were occasioned by local subsidences of the land.

All these lines of evidences, furnished by earthquakes, mountain chains, volcanoes and terrestrial oscillations, converge to one point, and, in combination, go far to prove that the earth's crust is relatively thin, and that its interior is fluid or viscous.

A priori considerations confirm this conclusion. If, as all believe, the earth was once a globe of molten matter which has cooled by radiation from the exterior, it seems impossible that the first formed crust could have sunk to the centre, and there laid the foundation of a solid structure, subsequently built up to the surface. Because, first, there is no probability that the superficial crust had a higher specific gravity than the underlying fluid; and, second, if its gravity were greater, and when broken up its fragments sank, they must soon have been melted by the greater heat below; and when, by this process, the outer zone of the earth had acquired a pasty consistence, its cohesion could not have been overcome by sheets of crust, even if a little denser. Hence, a cool, external crust, a hot, viscous zone and a hotter fluid nucleus seem logical necessities.

PROXIMATE CAUSES OF EARTHQUAKES.

Atmospheric Conditions.—If it is true, as claimed on the preceding pages, that earthquakes are the vibrations attending the folding and breaking of rocks which have been in a state of strain, it is evident that the provoking cause of any special paroxysm might be a comparatively trifling affair,—some feather that should break the camel's back. Thus, we have reason to believe that atmospheric conditions may precipitate these catastrophes. The pressure of the atmosphere on the earth's surface is 14.7 pounds to the square inch,—that is, a little over 2000 pounds to the square foot, or about 30,000,000 tons to the square mile. Now, it sometimes happens that the mercury oscillates two inches in the tube of a barometer in connection with some violent storm; and it is true that the areas of low and high pressure change position quite rapidly. Hence, if it should happen that the underlying rocks were from lateral pressure in a state of strain that had nearly reached the limit of resistance, a change of atmospheric pressure equivalent to two, or even one inch of mercury (equal to 1,000,000 or 2,000,000 tons per mile), might be the cause of a rupture. So, the popular belief, that peculiar atmospheric conditions have had an influence in causing earthquakes, is not so absurd as it might seem.

Accumulation of Sediments.—Another cause which has certainly operated to disturb the static equilibrium of the earth's crust, is the transfer of the products of erosion from the land to the bottom of an adjacent sea basin. Over all land areas where the rainfall is considerable, there is a constant wearing away of the surface by chemical and mechanical agents. About one-fourth of the material removed is dissolved and may be carried to the opposite side of the earth before it is precipitated; but the other three-fourths, in the form of gravel, sand and clay are simply held in suspension by running waters and are deposited as soon as their motion is arrested. Rivers, rivulets and shore waves are constantly engaged in transporting material from the land to the deeper water bordering the coasts; there spreading it to make new series of sedimentary deposits. As these accumulate they not only impose new burdens on the underlying rocks, but by acting as blankets and preventing the escape of heat, they promote the softening and weakening of a belt of sea bottom. This process has produced great changes in the surface topography of many continents, and it is credited with the formation of a number of littoral mountain chains. The blanketed belt of off-shore sea bottom, softened by heat, yields to lateral pressure, and is forced up in a series of faults and folds. There is little doubt that the loading of the sea bottom with the products of erosion has been one cause of the earthquake vibrations which have been so frequent along our Atlantic coast.

Periodicity of Earthquakes.—Very naturally an effort has been made to connect earthquakes with the changing relations of the sun and moon. M. Perrey, of Dijon, France, has tabulated the records of 2225 earthquakes which occurred between the years 306 and 1845. Of these he found that 1712 took place in winter and spring, and 1335 in summer and autumn. By Mr. Robert Mallet between 6000 and 7000 earthquake shocks are enumerated as having taken place in Europe only. Judging from all these it seems that earthquakes are a little more frequent when the attractions of the sun and moon are combined or opposed—that is at new and full moon—and when the earth is nearest the sun.

These data, although still defective, tend to support the theory of the fluidity of the interior of the earth, and confirm the testimony of volcanoes and the secular oscillations of the earth's crust.

Areas of Exemption.—Probably no part of the earth's surface has been always free from earthquakes. Nevada, Utah, New Mexico and Arizona were in Tertiary times more completely broken up and devastated by earthquakes and volcanoes than any other country known to us, but in that same region profound peace prevailed from the Cambrian to the Cretaceous age, many millions of years. Since the Tertiary the Colorado plateau has been remarkable for its stability. This is shown by the sandstone pillars several hundred feet high standing at the mouth of the Cañon of Chelly, and in the Colorado valley near the junction of Grand and Green Rivers. These columns have been formed by the slow removal of the material around them, a work of ages; and earthquakes would have brought them down in ruins, as they have shattered the monuments of Baalbeck, Tanis and Karnak.

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